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Research article

Exploring water use pathways under deep decarbonization scenarios in Canada at subnational scales using GCAM-Canada

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ABSTRACT

Canada is a water rich country with annual per capita freshwater withdrawals that rank among the highest in the developed world. As global and national decarbonization efforts progress, the implications of these energy and land system transitions for Canadian water resources remain underexplored. This study employs the integrated assessment model, GCAM-Canada, to project Canadian water use to 2050 in six sectors – municipal, manufacturing, irrigation, livestock, primary energy mining and, thermal power generation – across provinces and river basins under six combinations of socio-economic and climate mitigation scenarios. The resulting water use projections elucidate the relative impacts of socio-economic development, technological change, carbon emission restrictions, and direct air capture (DAC) technologies on water use at subnational scales. Additionally, the study quantifies virtual water embodied in exported Canadian crops and electricity to assess the effects of global decarbonization on local water resources. Our findings project national withdrawals to decline by 9 %–26 % by 2050 in all scenarios, although patterns vary by province and river basin. Conversely, water consumption increases across all scales. Net-zero climate policies produce potential trade-offs and synergies with water use in different provinces, emphasizing the need for regional considerations in climate policy formulation. Green and blue virtual water exports are projected to increase in all scenarios, although to a lesser extent under decarbonization, while electricity sector virtual water exports are projected to increase under global net-zero scenarios with rising U.S. demand for Canadian hydropower. Our study emphasizes the need for tailored solutions within Canada's broader climate and water management frameworks for a more sustainable future.

1. Introduction

Climate change presents an urgent challenge to both environmental and socioeconomic systems. The latest Intergovernmental Panel on Climate Change report (IPCC et al., 2023) emphasized that limiting global warming to 1.5–2 °C above pre-industrial levels requires reducing emissions to net-zero between 2050 and 2070, depending on the target, which will require large-scale transformations in energy and land systems and have far-reaching effects on other natural resources – particularly water (Pittock, 2011; Turner et al., 2018; Felder, 2014). While the emissions and economic dimensions of climate action have received considerable attention, fewer studies have examined the implications for water systems, despite their sensitivity to these structural shifts (Wild et al., 2021a; Ou et al., 2023). These interactions are especially important at subnational scales, where water, land, and energy availability and use differ by region and climate mitigation strategies are still evolving (Ou et al., 2023). Canada offers a compelling example of these dynamics.

Canada ranks 12th in global greenhouse gas emissions and has one of the highest per capita emissions rates among developed countries (Environment and Climate Change Canada, 2024). To reduce these emissions, the federal government enacted the Canadian Net-Zero Emissions Accountability Act (S.C. 2021, c. 22), committing the country to achieving net-zero emissions by 2050. The national target defines the overarching goal, but the means of its achievement could vary provincially, reflecting differences in energy systems, fuel choices, the availability both of other resources and of geological reservoirs for carbon storage, and economic priorities (Ou et al., 2023; Fuhrman et al.,

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2021). Certain mitigation strategies tend to reduce water use, such as promotion of wind and solar energy, while others could increase it, such as expansion of hydropower or deployment of direct air capture technology. These potential tradeoffs should be considered in climate policy decisions, particularly where resources like water are scarce (McCollum et al., 2018; Fuhrman et al., 2020).

In addition to the diversity of provincial climate mitigation pathways, water use in Canada is itself highly variable across regions and sectors (Agrawal et al., 2022). Sectoral demands are shaped by factors such as industrial activity, energy production methods and land use (Younis and Davies, 2023). In Ontario, over 80 % of water withdrawals cool nuclear power plants, while water use in Alberta is more balanced between cooling in thermal power plants and irrigation. Manufacturing and domestic water uses dominate in provinces like Quebec and British Columbia. Additionally, some sectors with a minor share of national water use are major regional users. For example, in 2017, oil and gas accounted for less than 1 % of Canada's total withdrawals but represented over 8 % of Alberta's and more than 50 % of the Mackenzie River basin's water use (Younis and Davies, 2023). This spatial heterogeneity adds complexity to assessing net-zero transitions and reinforces the need for subnational-scale analysis, where both mitigation strategies and sectoral demands could differ considerably.

Assessing the impact of decarbonization on future water use requires linking climate and energy policy pathways to both local and global water demand drivers. Local drivers including socio-economic factors like population growth and economic development, and technological advancements influence sectoral water use patterns over time – all independent of climate policy (Graham et al., 2018). For example, rising populations, incomes, and living standards increase domestic water use (Chen et al., 2022), and drive higher demand for food, energy, and goods, thereby raising the water requirements of agricultural and industrial sectors (Nechifor and Winning, 2017; Duarte et al., 2014). Technological advancements may reduce water intensity in some cases, but introduce new sources of demand in others (Fuhrman et al., 2020). Importantly, socio-economic drivers also influence decarbonization pathways by determining demands across industrial, energy, and land use sectors. These demands shape not only the scale of decarbonization required but also the types of mitigation strategies pursued, depending on available resources (Riahi et al., 2017), in turn influencing water use. Without considering these underlying domestic drivers, the influence of decarbonization on water systems may be misrepresented or underappreciated.

Global water demand drivers including socio-economics and climate and energy policies also shape regional water use through international trade (Zhong et al., 2023). The concept of virtual water, or the water embedded in traded goods and services, traces this regional and international exchange (Allan et al., 1994; Allan and Lant, 2003), and is especially relevant under global decarbonization scenarios, which are expected to substantially reshape land use and energy systems and thereby alter global demand for products from these sectors (Environment and Climate Change Canada, 2022). In Canada, agriculture and electricity are the two largest water-consuming sectors (Agrawal et al., 2022), and both contribute to international markets. In 2022, Canada was the fifth-largest exporter of agricultural and seafood products globally. Further, approximately 73 % of revenue from field crops and 57 % from horticulture came from exports (Agriculture and Agri-Food Canada, 2024), reflecting the sector's strong reliance on global demand. Moreover, about 7 % of Canadian electricity production was exported to the United States in 2024 (Natural Resources Canada, 2024), primarily from hydropower producing provinces. Assessing virtual water exports in these sectors reveals how global climate mitigation efforts can reshape external demand and, in turn, drive regionally different water impacts.

Despite a growing body of research on the resource implications of climate mitigation, the effects of decarbonization on water systems remain underrepresented. This paper identifies four key areas where current approaches can be improved. First, many existing studies have focused on national-level assessments which obscures the spatial heterogeneity of water use and policy implementation across subnational regions and river basins. Second, few studies have utilized a systems framework that can quantify the effects of both local and global drivers on subnational sectoral water use in decarbonization scenarios. Third, the water implications of emerging mitigation strategies, such as direct air capture, remain unexplored in the Canadian context, despite an expected rise in their deployment rate and their potential to significantly alter water and energy demands (Fuhrman et al., 2020). Fourth, although virtual water flows are increasingly recognized as important for linking trade and water use, they are not often examined alongside decarbonization policies.

To address these gaps, this study presents the first comprehensive analysis of water use under deep decarbonization across all Canadian provinces and major river basins, capturing their spatial heterogeneity across six key water-using sectors. Unlike most existing work, it employs a systems-based integrated assessment model to quantify the effects of both local and global drivers on future water demand. It also introduces a subnational assessment of virtual water exports in the agriculture and electricity sectors, demonstrating effects of global climate mitigation on local water resources via trade, and for the first time in Canada, evaluates the water implications of direct air capture deployment. These contributions enable a cross-sectoral, multi-scalar, and spatially detailed understanding of how net-zero transitions could affect regional water use in Canada.

For this study, we apply GCAM-Canada, a provincially disaggregated version of the Global Change Analysis Model (GCAM), which integrates five human–environment systems: energy, land, water, economy, and climate. Using this framework, the study investigates four core research questions.

1) What are the effects of population and economic development on sectoral water use in Canada at the provincial and river basin scales in the absence of climate policy?
2) How does the introduction of net-zero targets impact water resources at the same scales?
3) Does regional implementation of the water intensive direct air capture technology in efforts to reach net-zero lead to notable changes in sectoral water use?
4) Finally, how do international market shifts in the agricultural and electricity sectors, particularly in response to global decarbonization efforts, influence local water use in Canada?

This paper addresses the four questions through a simulation of water withdrawals and consumption across six major sectors to 2050 through a combination of six socio-economic and climate mitigation scenarios. The first question establishes a reference case driven by socio-economic and technological change in the absence of climate mitigation policy. The second evaluates how deep decarbonization scenarios affect water use through transformations in land and energy systems through a comparison with the first scenario. The third explores sectoral water use implications of widespread direct air capture deployment, an emerging but underexamined technology in Canadian water studies. The final question assesses how shifts in international trade driven by global mitigation policies will influence local water systems through virtual agricultural and electricity sector water trades.

2. Literature review

Several studies have estimated global future water use at a national scale using Integrated assessment models (IAMs). They have projected future water use for specific sectors and addressed questions related to the impacts of climate change and mitigation policies on land use and agricultural water use (Chaturvedi et al., 2013; Huang et al., 2019), effects of groundwater depletion on irrigation and crop production globally (Turner et al., 2017), withdrawals in the municipal sector under multiple socio-economic and water conservation scenarios (Hejazi et al., 2013), and withdrawals and consumption in the electricity sector under different socio-economic, climate mitigation policy, and water conservation scenarios (Davies et al., 2013; Kyle et al., 2013; Liu et al., 2015). Other studies have projected water use across multiple sectors to analyze potential future dynamics of Water-Energy-Food (WEF) systems in water-limited regions (Kim et al., 2016), assess the impacts of different socio-economic factors on water uses (Hejazi et al., 2014a; Bijl et al., 2016), or quantify future water scarcity under alternative climatic and socio-economic scenarios (Hejazi et al., 2014b; Graham et al., 2020a). Fewer studies have projected water use sub-nationally with IAMs. Some have focused on administrative boundaries in the United States (Ou et al., 2023; Binsted et al., 2022; Ganji et al., 2024) or Peru (Correa et al., 2022), while others have analyzed the WEF dynamics within river basins (Zeng et al., 2022; Wild et al., 2021b).

In the Canadian context, several recent studies have applied an IAM approach to sectoral water use under different climate mitigation scenarios either at national or provincial scales. Nationally, Kuling et al. (2022) used an IAM to project irrigation water use with bioenergy adoption under a net-zero scenario and found that water demands could increase substantially under some conditions. Gupta et al. (2021) analyzed the impacts of electricity sector decarbonization on water consumption and reported 8 % less consumption than a current policy scenario. At the provincial scale, the identified studies focused on Alberta and Saskatchewan, regions central to Canada's fossil fuel production and therefore key to national net-zero transitions. In Alberta, Ali (2018) forecasted future primary energy mining and electricity sector water use and found increasing consumption in all studied energy scenarios, especially those involving biofuels. Agrawal et al. (2018) similarly found increasing electricity water use by 2050 in eight of nine decarbonization scenarios. More recently, Moraes Coraça et al. (2025) assessed the implications of hydrogen based decarbonization pathways on water resources from 2026 to 2050 and reported a significant associated water footprint. In contrast to the previous studies that reported water tradeoffs, the study by Wu et al. (2021) in Saskatchewan projected a reduction in water use, identifying a synergistic effect between wind energy promotion and decreased industrial water demands.

Many international studies have used input-output models to quantify and analyze present-day interregional agricultural trade through the concept of virtual water (Fu et al., 2021; Liu et al., 2022). However, relatively fewer studies have projected virtual water trade into the future. Gravity models of trade in agricultural products (Ashktorab and Zibaei, 2021), coupled in one case with a stochastic model (Sartori et al., 2017), have been applied under different socio-economic and climate scenarios, while GCAM was used to quantify future green and blue virtual water trades in global agricultural products at a national scale (Graham et al., 2020b) and in electricity sector water trade within the U.S. (Graham et al., 2021). No studies have projected future virtual water trades for Canada at subnational scales to assess effects of decarbonization on virtual water trades.

3. Methods

This study applies GCAM-Canada, a spatially disaggregated version of the Global Change Analysis Model (GCAM v5.3), to evaluate subnational water use interactions under multiple decarbonization pathways. GCAM is an open-source IAM developed by the Joint Global Change Research Institute (JGCRI) that simulates long-term interactions among five interconnected systems: energy, water, land and agriculture, economy, and climate. GCAM operates as a partial equilibrium model, solving iteratively in 5-year time steps to find market prices that balance supply with demand across all sectors and regions. GCAM incorporates inputs such as historical data, future assumed trajectories of socio-economic development, and technology-specific cost and efficiency parameters. Historical data spanning 1975 to 2015 (model base year) are used to calibrate the model, ensuring consistency between simulated and observed values for key variables such as energy production, land use, water withdrawals, and GDP throughout the calibration period. The model uses a recursive dynamic structure, where decisions in each time step are based on system states and market conditions from the previous period. The 2015 base year represents the initial system state from which all future projections, extending to 2100, are simulated. Model outputs include projections of resource use, emissions, land use change, and water withdrawals and consumption by sector. Systems are represented at multiple spatial resolutions: energy and economic systems are simulated in 32 geopolitical regions, land use is divided into 384 land units, and water is represented in 235 river basins. For further technical documentation and details on model structure, see Calvin et al. (2019) and the JGCRI documentation (JGCRI, 2022).

3.1. GCAM-Canada

GCAM-Canada is a geographically disaggregated version of GCAM v5.3 that represents the individual socio-economic, energy, and emissions systems of its 10 provinces and 3 territories. GCAM-Canada supports subnational analysis within a globally linked framework, enabling assessments of how local and global drivers and policies affect subnational resource systems. An advancement to GCAM-Canada's water sector is the spatial disaggregation of water demands to the provincial/territorial scale, which has enabled a subnational analysis of water-energy-land interactions. Details on the implementation are provided in Section 3.2. In addition to spatial disaggregation, this version includes two key features relevant to this study that are not part of the public core model. First, hydropower generation is modeled endogenously at the provincial scale, allowing it to compete with other electricity sources based on relative cost and resource availability (Arbuckle, 2023). This feature is particularly important for capturing the implications of future hydropower deployment under decarbonization policies and its effect on evaporative water consumption. Second, GCAM-Canada incorporates a detailed electricity trade structure that simulates interprovincial flows as well as bilateral electricity exchanges between Canadian provinces and the United States (Chiappori et al.). This structure permits estimation of virtual water exports associated with electricity trade (refer to the supplementary material for more information on this feature).

3.2. Water demand structure in GCAM-Canada

This section describes the approach to spatially disaggregating water demands in GCAM-Canada to the provincial scale. Water demands in GCAM are computed for six key sectors: domestic, manufacturing, electricity, irrigation, livestock, and primary energy mining. For sectors modeled at the provincial scale (i.e. domestic, manufacturing, and electricity), water demands are directly calculated within each province or territory. For sectors that remain modeled at the national or river basin scale in GCAM-Canada (i.e., livestock, primary energy mining, and irrigation), national or basin-level demands are allocated to provinces post-simulation using fixed historical shares from 2015, the last historical year in the model. While this method assumes a static spatial distribution and therefore does not account for potential future shifts in agriculture, livestock, or mining activity, it aligns with methods used in previous GCAM-based studies (Binsted et al., 2022). The spatial resolution of sectoral demand estimation is illustrated in Fig. 1. Historical water use data employed in this study are described in Younis and Davies (2023).

The methods to estimate water demands in GCAM vary by sector. Domestic and manufacturing water demands are calculated based on exogenous inputs, specifically provincial population and GDP trajectories, which directly determine household and industrial water needs (Hejazi et al., 2014a). In the remaining four sectors, water demands are calculated depending on two components: (1) water use intensity per unit of production or activity, and (2) the magnitude of sectoral activity

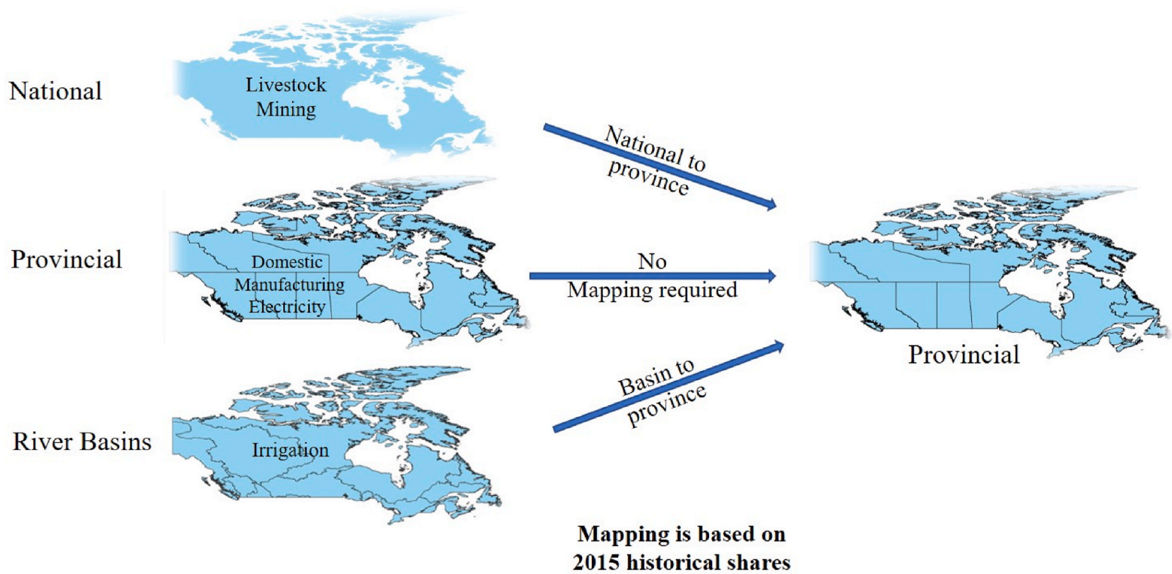

Fig. 1. spatial scales of water demand calculation for each sector in gcam-canada.

at each time step. Water intensity coefficients are derived from published literature for the agriculture (Mekonnen et al., 2011), livestock (Mekonnen et al., 2010), electricity (Macknick et al., 2012), primary energy mining (Maheu, 2009), hydropower (Bakken et al., 2017), and direct air capture (DAC) (Fuhrman et al., 2021) sectors. Sectoral activity levels are determined endogenously within GCAM based on interactions among sectors and regions. For example, electricity sector water use is driven by end-use electricity demand (influenced by socio-economic assumptions), but is also influenced by endogenous decisions about fuel mix and generation technologies, which are in turn impacted by carbon policies, resource costs, and technology preferences. Similarly, water demand for crops and livestock is influenced not only by food demand (driven by exogenous assumptions like population and income) but also by endogenous dynamics such as land competition, crop profitability, and regional agro-climatic suitability. Water requirements for primary energy mining depend on the scale and type of fossil resource extraction, which respond to global energy demand and fuel price signals (see Hejazi et al. (2014a) and Chaturvedi et al. (2013) for more details about water demands in GCAM).

Water supply in GCAM is allocated from three sources, each represented by a basin-specific resource price curve. The first source is the renewable water supply, which includes surface runoff and groundwater recharge. For this study, we used existing output from the global hydrological model Xanthos (Li et al., 2017), forced with WFDEI meteorological data, to obtain annual runoff volumes (in km^3) for each river basin over the 1970–2010 period. The historical average runoff across this period was calculated for each basin and held constant in all future years as the estimate of renewable water availability. GCAM assumes that a baseline volume of renewable water is available at a nominal cost, with marginal prices increasing as the extraction of additional supply necessitates infrastructure investments (Kim et al., 2016). The second source is non-renewable groundwater (or 'fossil water'), represented by resource curves with escalating extraction costs based on aquifer depletion. Availability was derived from groundwater levels and soil characteristics (Turner et al., 2017). Finally, the third source is desalination, which is available in coastal regions and provinces at significantly higher costs, reflecting its high energy and capital requirements. GCAM allocates water across sectors and basins by minimizing total system cost, considering sectoral demands, the available water supply, and marginal water prices derived from basin specific supply curves. When demand exceeds the availability of low-cost water, the model turns to higher-cost sources such as fossil water or desalination. Under water scarcity, increasing costs may drive shifts in sectoral behavior, such as changes in crop selection, fuel choices, or technology adoption, to reduce water use.

3.3. Scenario design

This study employed a scenario matrix that combines two socio-economic pathways with three emissions trajectories to situate mitigation strategies within a plausible range of socio-economic futures. The two socio-economic scenarios followed the Shared Socio-economic Pathways (SSPs) narratives described in O'Neill et al. (2014).

- SSP2 represents a "middle-of-the-road" development pathway in which population and economic growth follow historical trajectories; and
- SSP5 represents a high-growth future with rapid economic expansion and higher population levels by 2050.

These two socio-economic pathways were then paired with each of the following emissions scenarios.

- REF: a reference scenario without climate policy, used to benchmark water use in the absence of mitigation;
- NZ: a net-zero emissions scenario in which all 32 GCAM regions reach net-zero greenhouse gas emissions by a specified year; and
- NZDAC: a variation of the NZ scenario that includes DAC as an additional mitigation option, subject to technology costs, energy and water requirements, and geological storage availability

This two-by-three combination resulted in six scenarios. The two reference scenarios (REF_SSP2 and REF_SSP5) provided baseline projections of water use and were used as reference points to distinguish the specific contributions of mitigation policies from broader socio-economic influences in each development trajectory. Socio-economic assumptions for the Canadian water sector in both scenarios are tabulated in SI3 and followed Graham et al. (2018). Both scenarios assumed technological improvements in water use efficiency across the domestic, manufacturing, and irrigation sectors. For the domestic sector, SSP5 included lower price elasticity to reflect higher income and quality-of-life assumptions. In the electricity sector, new thermal power plants were assumed to adopt no more than 10 % once-through cooling and at least 10 % dry cooling, with the remainder relying on recirculating systems, following assumptions in Macknick et al. (2012).

For both net-zero scenarios, a national climate policy was implemented by imposing economy-wide emissions constraints for Canada at each model time step, consistent with achieving net-zero by 2060. All provinces and territories were assumed to cooperate in meeting the national target, and no province-specific policies were imposed. Instead, GCAM endogenously determined a carbon price through its iterative market equilibrium mechanism that would obey the national constraint. This national carbon price was applied uniformly across all provinces and influenced provincial mitigation decisions such as fuel switching, energy efficiency improvements, and the deployment of carbon capture and storage (CCS). These decisions varied regionally based on differences in mitigation costs, resource availability, and energy system structures. In NZDAC scenarios, DAC technologies were introduced as an additional mitigation option, constrained by technology costs, energy and water inputs, and the availability of suitable geological storage.

To simulate the effects of global decarbonization on local resources, the NZ and NZDAC scenarios also included emissions constraints for all other 31 GCAM regions. The adopted emissions reduction structure assumed that all regions met their nationally determined contributions under the Paris Agreement by 2030, after which Annex I countries would reduce emissions linearly to zero by 2060, and non-Annex I countries by 2080. The distinction between the environmental targets of Annex (I) and non-Annex (I) countries followed the classification adopted in Bergero et al. (2022), where Annex (I) countries were assumed to have the financial resources and capabilities to decarbonize their economies in a shorter time period than Annex (II) countries. Although these assumptions meant that the planet would reach net-zero beyond 2050 for all regions, our analysis focused on mid-century outcomes. Further, these targets were intended to represent illustrative mitigation pathways rather than represent the only approach to net-zero emissions. While the stringency of the emissions targets may influence the magnitude of projected water system responses, quantifying these effects was beyond the scope of this study.

3.4. Virtual water exports estimations

A post-processing analysis adapted from Graham et al., (2020b, 2021) was applied to estimate the volume of virtual water exports embedded in Canada's agricultural and electricity trade based on model outputs for production, water use, and trade. Agricultural water exports were estimated at the river basin scale, consistent with the representation of land-use and crop production in GCAM-Canada. For the electricity sector, virtual water exports were calculated at the provincial scale to align with the spatial resolution of electricity generation in the model. The methods used in each case are described in the following sections.

3.4.1. Agricultural virtual water export estimation

Agricultural virtual water can be classified into two types: green water (GVW), which refers to soil moisture from precipitation used in rainfed agriculture, and blue water (BVW), which refers to surface and groundwater used in irrigated agriculture. Although green water is not directly controlled or allocated (unlike blue water), it represents a vital component of agricultural water use, particularly in Canada, where over 98 % of cropland is rainfed (Statistics Canada, 2023). The analysis included both types for a more comprehensive assessment of the effects of Canadian crop exports on local water resources under future decarbonization scenarios.

In GCAM, trade in agricultural products occurs through a global market structure. Basin-level production from all regions is aggregated into a common pool, which is then allocated to meet demands across the 32 GCAM regions. While water consumption and crop production are reported at the basin level, crop demand and trade flows are only tracked for the 32 model regions. As a result, the model does not specify which basins supply domestically consumed or exported products. To resolve this spatial mismatch, we assumed each of the thirteen (13) river basins in Canada (shown in Fig. 2) contributed a share of the total domestic demand for a given crop, with the remainder of production exported internationally. These shares were assumed to be proportional to each basin's production relative to the total production for a given crop across all basins in Canada. Hence, the magnitude of net exports $Ag\_E_{b,c,g}$ in tonnes of a given crop c, grown using growing method g (irrigated or rainfed), from each basin b, was computed as the difference between the total production $P_{b,c,g}$ and the basin's production share directed towards domestic national demand as shown in Equation (1):

$$Ag\_E_{b,c,g} = P_{b,c,g} - \left(D_{nat,c} \times \frac{P_{b,c,g}}{\sum_{b}^{n} P_{b,c}} \right) \tag{1}$$

Where.

- $P_{b,c,g}$ is the total crop production (in tonnes) for crop c, method g, and basin b;
- $D_{nat,c}$ is the national crop demand (in tonnes) for crop c; and
- $n = 13$ is the number of river basins within the Canadian region.

A basin was considered a net exporter of a crop if there was a surplus (i.e. a positive value from Equation (1)). Net virtual water exports $Ag\_VWE_{b,c}$ in km^3 were then calculated as the product of water consumption per unit crop production in km^3/tonne and net crop exports, as shown in Equation (2):

$$Ag\_VWE_{b,c} = \frac{WC_{b,c}}{P_{b,c}} \times Ag\_E_{b,c} \tag{2}$$

Where.

- $WC_{b,c}$ is total water consumption (in km^3) for basin b and crop c; and
- $P_{b,c}$ is total crop production (in tonnes) for basin b and crop c.

Green water consumption and rainfed crop production were employed in Equation (2) when calculating GVW exports, while blue water consumption and irrigated production were used to estimate BVW exports. The shares of blue/green water and irrigated/rainfed crops are provided by GCAM (Chaturvedi et al., 2013).

3.4.2. Electricity virtual water export estimation

Electricity virtual water (EVW) exports refers to the volume of water consumed during the generation of electricity that is subsequently exported. The adopted methodology is used to estimate EVW exports from all Canadian provinces to the United States, Canada's only international electricity trade partner, based on water consumption and electricity trade outputs from GCAM-Canada. EVW exports by fuel type f for each exporting province i and importing region j were calculated as the product of water consumption per unit electricity generation (in km^3/EJ) and the volume of electricity exports (in EJ), following Equation (3):

$$EVW_{i,j,f} = \left(\frac{WC_{i,f}}{ElecGen_{i,f}} \right) \times \left(\frac{ElecGen_{i,f}}{\sum_{f}^{F} ElecGen_{i,f}} \times ElecExp_{i,j} \right) \tag{3}$$

Where.

- $WC_{i,f}$ is the total water consumption for electricity generation in province i by fuel f (in km^3);
- $ElecGen_{i,f}$ is the total electricity generation in province i by fuel f (in EJ);

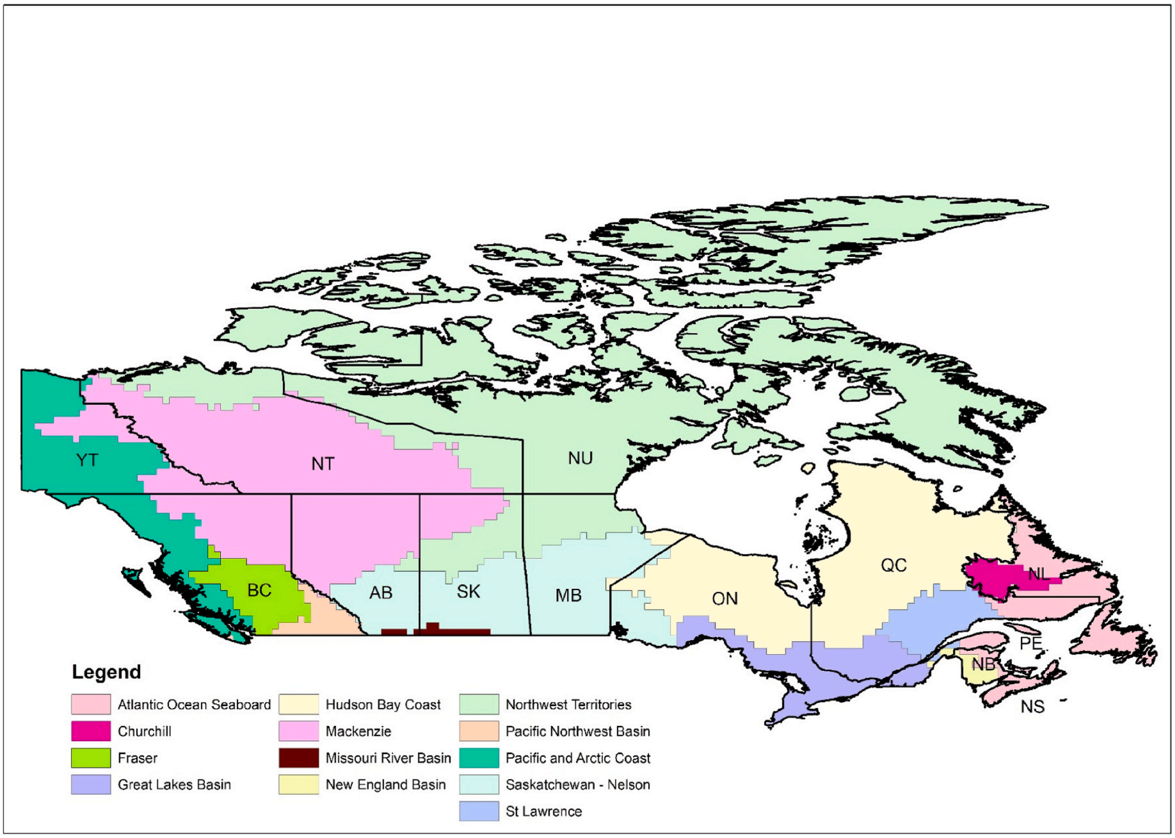

Fig. 2. The 13 Canadian river basins included in GCAM Canada.
*AB: Alberta, BC: British Columbia, MB: Manitoba, NB: New Brunswick, NL: Newfoundland & Labrador, NS: Nova Scotia, NT: Northwestern territories, NU: Nunavut, ON: Ontario, PE: Prince Edward Island.

- $ElecExp_{i,f}$ is the total electricity exported from province i to importing region j (in EJ); and
- F is the total number of fuels used for electricity generation.

The equation assumed that the share of electricity exports attributed to each fuel type is proportional to that fuel's share of total generation within the exporting province. Total EVW exports from each province i to each importing region j were then calculated by summing EVW exports over all fuel types f, as shown in Equation (4):

$$EVW_{i,j} = \sum_{f=1}^{F} EVW_{i,j,f} \quad (4)$$

Note that both Equations (3) and (4) represent a generic form applicable to estimating EVW trade flows between any two regions. In our analysis, we focused on trade flows from Canadian provinces to the U.S.; therefore, the importing region j was held constant as the U.S.

4. Results and discussion

The sections below present findings and analysis for the four research questions listed in the introduction. Section 4.1 establishes a policy-neutral reference case, the REF_SSP2 scenario, which reflects current trends in population growth, economic development, and water-saving technologies and omits climate mitigation efforts. Section 4.1 also compares REF_SSP2 with REF_SSP5 to explore how accelerated population and economic growth intensify water demands and shift sectoral patterns. Section 4.2 compares results from the reference scenarios with those of the net-zero scenarios to illustrate effects of deep decarbonization on water resources and includes the effects of DAC as an emission mitigation option, which addresses research questions 2 and 3. Section 4.3 shifts to a global lens, examining how international decarbonization efforts influence Canada's water resources through changes in virtual water exports. We analyze GVW and BVW exports as well as EVW exports to reveal how evolving global demand and emission constraints feed back into local water pressures in Canada, addressing research question 4.

4.1. Reference water use scenarios

4.1.1. Water withdrawals in the REF scenarios

Absent decarbonization policies, future water withdrawals in Canada were shaped by two counteracting drivers: 1) population and economic growth, which increased water demands, and 2) water saving technologies, which improved water use efficiency. In the REF_SSP2 scenario, the interplay of both dynamics produced different results at different spatial scales. Total national withdrawals decreased by 26 % from 2015 to 2050, as shown in the first column of Fig. 3, largely because of the declining water intensity of the electricity sector. As newer thermal power plants adopted less water-intensive cooling technologies (Davies et al., 2013), the share of electricity withdrawals from total withdrawals fell from 67 % in 2015 to 46 % by 2050. At the same time, population growth (refer to Figure SI2.F1 in SI) drove increases in domestic, manufacturing, and irrigation withdrawals, with their respective shares rising from 14 %, 10.5 % and 5 % in 2015 to 24 %, 18 % and 8 % in 2050.

Provincial and river basin results revealed considerable heterogeneity in their responses to these drivers, depending on their dominant water-using sectors, as presented in the first columns of Figs. 3 and 4. Some regions mirrored the national trend, while others diverged, largely because of differences in sectoral composition and the nature of technological improvements. In particular, provinces where electricity withdrawals historically dominated saw substantial reductions, as the

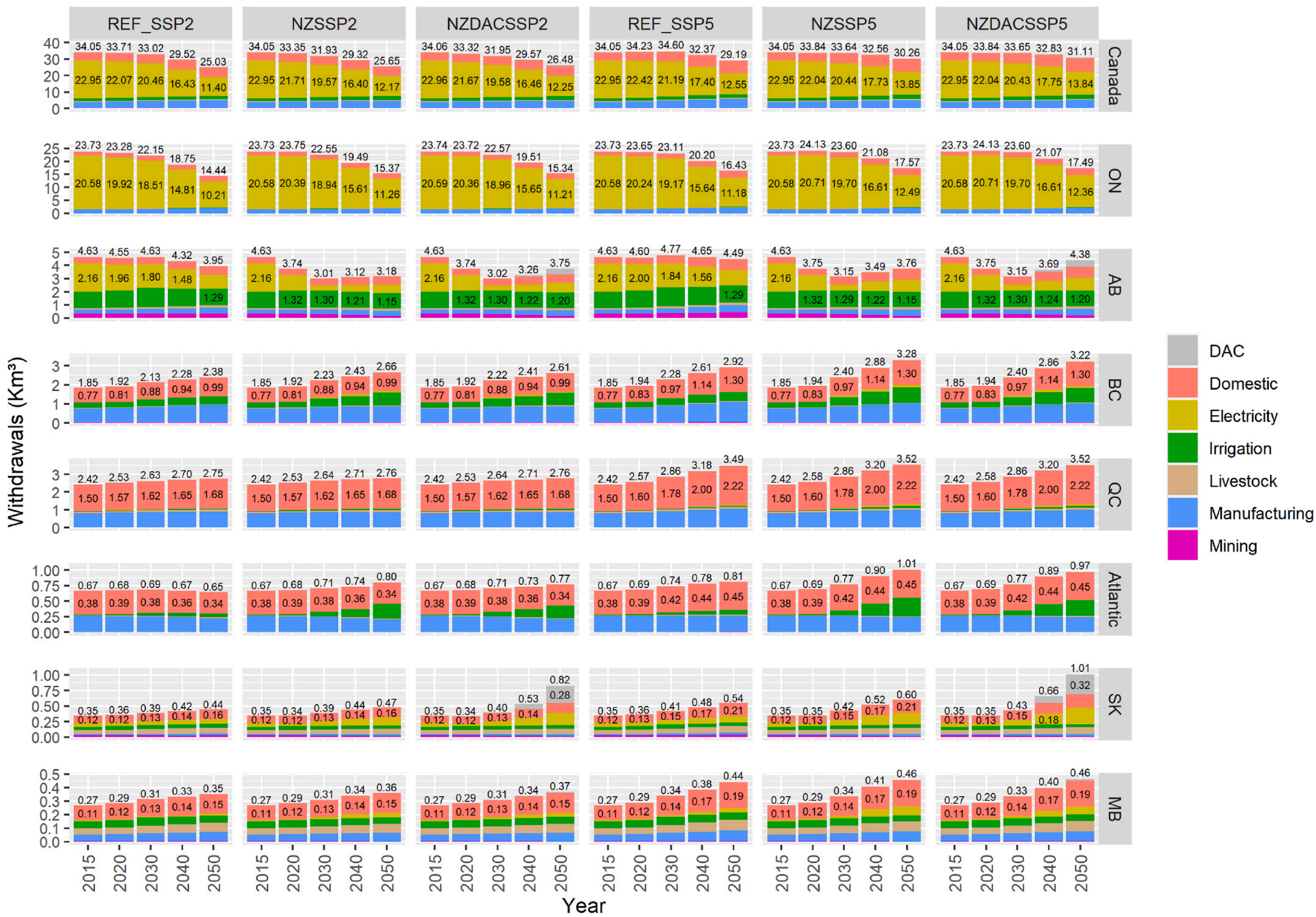

Fig. 3. National and Provincial water withdrawals by sector in all scenarios between 2015 and 2050
*ON: Ontario, AB: Alberta, BC: British Columbia, QC: Quebec, Atlantic: All Atlantic provinces, SK: Saskatchewan, MB: Manitoba
Text shows withdrawals by highest withdrawal sector on bar charts and total withdrawals above each bar.

shift from once-through to recirculating cooling systems significantly lowered withdrawal intensity. This pattern was evident in Ontario, which had the highest magnitude of withdrawals and followed the national trend: electricity sector withdrawals fell by 50 % from 2015 to 2050, with the adoption of low water-intensity cooling technologies (i.e. recirculating systems) and a 587 % increase in wind generation by 2050, which does not require cooling water (refer to figure SI5.1 F1 for provincial electricity generation by fuel). The Great Lakes River basin, where Ontario accounted for ~85 % of the total withdrawals, followed the same trajectory. Alberta and the Saskatchewan-Nelson basin, where Alberta's withdrawals accounted for ~83 % of the total, also exhibited overall declines, with a 15 % decline in withdrawals in Alberta through similar shifts in cooling technologies.

In contrast, no similarly transformative efficiency assumption existed for other sectors, such as irrigation, manufacturing, or domestic use, where the assumed technological improvements were more incremental. As a result, regions with water use concentrated in these other sectors experienced rising withdrawals, as population and economic growth outpaced efficiency gains. Manitoba, British Columbia, Saskatchewan, and Quebec exhibited this trend, and experienced rising total withdrawals between 2015 and 2050 of 31 %, 29 %, 27 %, and 13 % respectively, with a rise in domestic (between +12 % and +33 %) and manufacturing (between +11 % and +39 %) withdrawals compounded by a 42 % increase in irrigation withdrawals in British Columbia. This increase resulted from population growth and economic development and corresponding increases in food demands. The corresponding river basins witnessed the same pattern, including the Fraser, Pacific Northwest, and Pacific & Arctic in British Columbia, and the Hudson Bay and St. Lawrence in Quebec (see Fig. 4).

The REF_SSP5 scenario, with its high-growth development pathway, exhibited similar sectoral dynamics but amplified the magnitude of change. Although the decreasing trend of total water withdrawals persisted in REF_SSP5, the slope was milder, with national withdrawals projected to be 18 % higher than REF_SSP2 by 2050 because of steeper increases in the manufacturing, domestic, and agricultural sectors, alongside a smaller reduction in electricity sector use relative to REF_SSP2. These shifts were driven by larger demands for food crops (22 % higher), electricity (30 % higher) and manufactured products resulting from a higher population (22 % higher), and elevated standards of living compared to REF_SSP2. Although water-saving technologies continued to improve efficiency, they were outpaced by the scale of growth in sectoral demands.

In REF_SSP5, provinces and basins that showed increasing water use under REF_SSP2 experienced amplified growth, while those with declining trends saw milder reductions. Ontario, Alberta, and the Great Lakes basin still showed decreasing trends, but withdrawals remained 14–16 % higher than in REF_SSP2 by 2050. British Columbia, Saskatchewan, Manitoba, and Quebec continued to exhibit increases in water use, magnified under the SSP5 pathway. Additionally, withdrawals increased by 25 % in the Mackenzie basin because of oil sands expansion in Alberta (refer to figure SI5.3 F3 for projected oil and gas production).

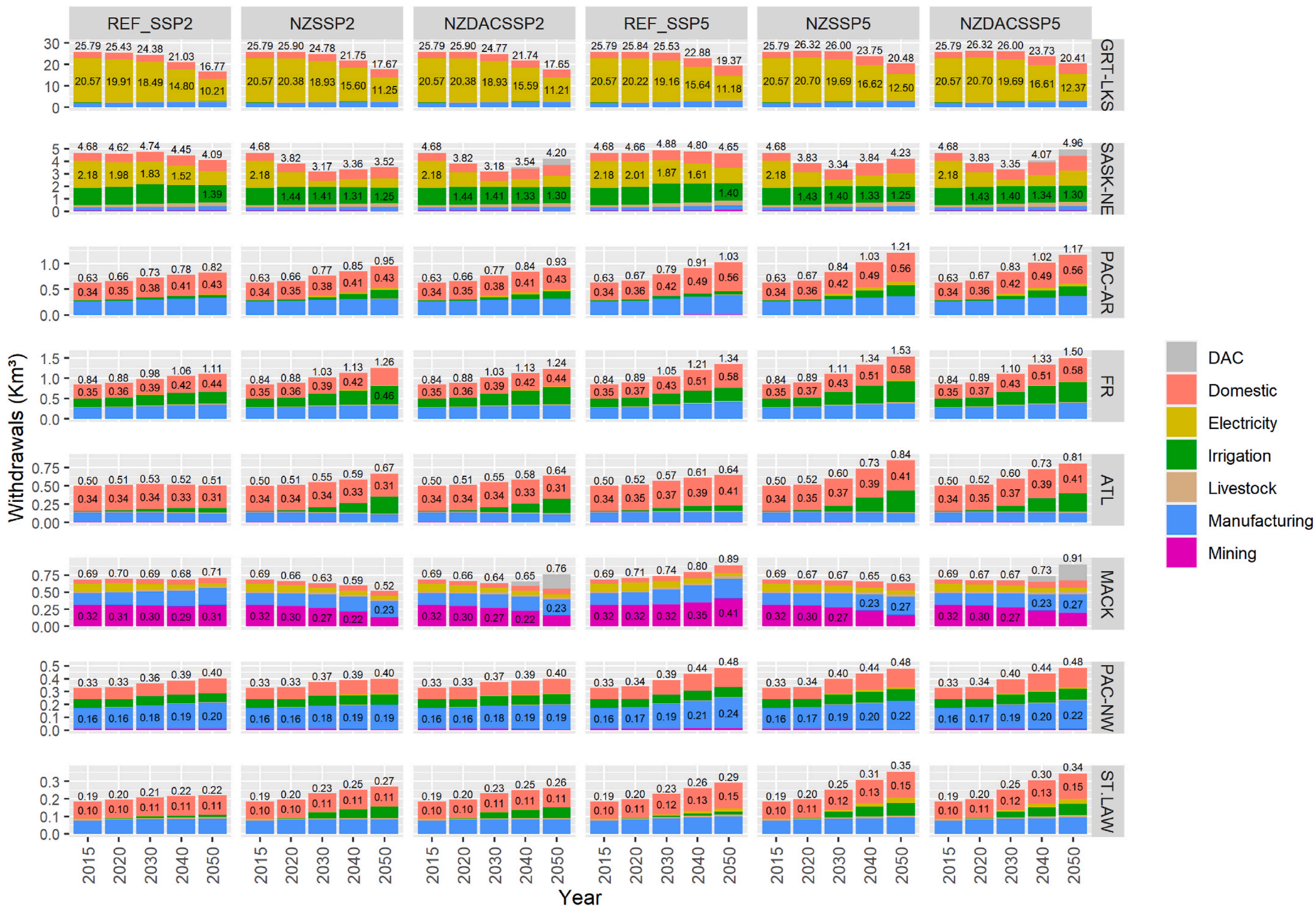

Fig. 4. Water withdrawals by sector for river basins with the highest withdrawals in all scenarios between 2015 and 2050
*GRT-LKS: Great Lakes, SASK-NEL: Saskatchewan Nelson, PAC-AR: Pacific Arctic, FR: Fraser, ATL: Atlantic, MACK: Mackenzie, PAC_NW: Pacific Northwest, ST. LAW: Saint Lawerence
Text shows withdrawals by highest withdrawal sector on bar charts and total withdrawals above each bar.

4.1.2. *Water consumption in the REF scenarios*

In the REF_SSP2 scenario, total water consumption in Canada increased by 18 % between 2015 and 2050, despite an overall decline in water withdrawals, primarily because of evaporative losses from hydropower reservoirs and, to a lesser extent, evapotranspiration from irrigated agriculture. By 2050, the electricity and irrigation sectors accounted for 67 % and 12 % of national water consumption, respectively. As one of the world's leading hydropower producers, Canada generated about 57 % of its electricity from hydropower in 2015, and national hydropower production increased by 15 % during the study period. Consequently, electricity-related water consumption rose by 13 %, while irrigation-related consumption increased by 21 % as shown in Fig. 5.

Regional patterns reflected the spatial distribution of hydropower generation and irrigated agriculture, and the provinces and basins with the largest hydropower output experienced the most significant increases. Specifically, Ontario showed the largest absolute increase in water consumption, driven by a 24 % expansion in hydropower in the Great Lakes and Hudson Bay basins, while Manitoba recorded a 24 % increase in total water consumption driven by a 23 % rise in hydropower production in the Saskatchewan–Nelson basin. In contrast, consumption rose in the Mackenzie (+31 %) and Fraser (+38 %) basins of British Columbia with growth in both hydropower and irrigated crop production. In Alberta, agriculture drove the increases, with irrigation and livestock water consumption rising by 17 % over the study period.

In REF_SSP5, greater energy and food demands led to national water consumption levels that were 16 % higher than REF_SSP2. The electricity sector accounted for 64 % of this additional use, fueled by a further 15 % rise in hydropower production. The remaining increase came from the domestic (13 %), irrigation (7 %), and manufacturing (7 %) sectors. Together, Quebec, British Columbia, Ontario, and Alberta contributed 86 % of the national increase, and hydropower expansion in the Hudson Bay and St. Lawrence basins within Quebec was responsible for the largest rise, followed by increases in the Fraser and Mackenzie basins in British Columbia.

4.2. *Effects of deep decarbonization policies*

4.2.1. *Water withdrawals in the NZ scenarios*

The introduction of net-zero policies altered energy and land use systems and consequently affected electricity and agricultural sector withdrawals. Although they caused national withdrawals only to increase marginally (∼2 %) from the REF_SSP2 scenario by 2050, net-zero policies had two notable effects on national sectoral water use. First, they encouraged a shift away from fossil fuels as an energy source (16 % lower), especially for residential and industrial uses, toward a more electricity-dependent system. This resulted in an 8 % higher thermal power generation and a corresponding 7 % higher water withdrawals for electricity by 2050 compared to REF_SSP2. Further, net-zero policies caused a 3.9-fold increase in purpose-grown biomass crop production – as an alternative to fossil fuels and because of its negative emission potential when employed with CCS (i.e. Bioenergy Energy with Carbon

Fig. 5. National and Provincial water consumption by sector in all scenarios between 2015 and 2050
*ON: Ontario, AB: Alberta, BC: British Columbia, QC: Quebec, Atlantic: All Atlantic provinces, SK: Saskatchewan, MB: Manitoba
Text shows Consumption by highest Consumption sector on bar charts and total withdrawals above each bar.

Capture and Storage or BECCS) – which increased irrigation withdrawals by 19 % nationally compared to REF_SSP2 by 2050.

These national-level changes translated into diverse subnational outcomes, as presented in the second column of Figs. 3 and 4, with the differences shaped by the type and scale of energy transitions and land-use responses. Some provinces experienced elevated water withdrawals compared to REF_SSP2 because of elevated cooling water requirements from thermal power plants. For example, total withdrawals in Ontario were 6 % higher for NZSSP2 by 2050, because of a 10 % larger electricity withdrawal despite the 22 % decrease in thermal power generation compared to REF_SSP2. A shift in the composition of Ontario's thermal mix towards nuclear energy away from natural gas combined cycle generation in REF_SSP2 could explain the increase. Although both technologies were assumed to employ recirculating cooling systems, nuclear plants have higher water withdrawal intensities per unit of electricity generated (Macknick et al., 2012), leading to an overall rise in electricity water withdrawals. Similarly, Saskatchewan saw a 7 % increase because of higher cooling demands for thermal plants with CCS, which constituted 95 % of electricity generation from thermal sources. Other provinces experienced higher withdrawals under NZSSP2 primarily because of increased irrigation demands associated with the expansion of purpose-grown biomass. This is evident in British Columbia, Nova Scotia, and Prince Edward Island, which experienced elevated withdrawals compared to REF_SSP2, with increased irrigation withdrawals particularly in the Fraser, Pacific-Arctic, and Atlantic river basins as shown in Fig. 4, where irrigated biomass production rose by 242 %, 374 %, and 339 %, respectively.

In contrast to provinces with rising withdrawals, some regions experienced an overall decline in water use under NZSSP2. This pattern primarily occurred in regions where renewable energy expanded, since it does not require water for cooling. For example, Alberta, where withdrawals primarily from the Saskatchewan-Nelson and Mackenzie basins, exhibited a synergistic trend in the NZ scenario: withdrawals gradually declined until 2030 and then grew modestly afterwards, which resulted in a 20 % reduction between 2015 and 2050. The early decline was driven by the retirement of coal-fired power plants and their replacement with wind energy, which led to an 82 % drop in electricity withdrawals between 2015 and 2030. Although thermal generation increased by 58 % after 2030, largely through CCS-equipped facilities, the corresponding rise in withdrawals was relatively modest compared to the drop from 2015 to 2030 because newer plants employed low water intensity cooling technologies. Basin-level patterns reflected this trend, with withdrawals falling by 14 % in the Saskatchewan-Nelson basin and 27 % in the Mackenzie basin by 2050. The trends in NZSSP5 matched those of the NZSSP2 scenario across all provinces and basins, although with greater withdrawals in NZSSP5 because of higher sectoral use in SSP5.

4.2.2. *Water withdrawals in the NZDAC scenarios*

The addition of DAC technologies for climate change mitigation yielded a small increase in withdrawals (~3 % by 2050) at the national level from NZSSP2, as shown in the third column of Fig. 3, primarily driven by the direct water requirements of the DAC process and the additional electricity generation needed to power it. As DAC deployment was assumed to occur in regions with available geological storage, its impact was concentrated in western Canada —particularly in Alberta and Saskatchewan.

Both provinces experienced higher withdrawals than in NZSSP2. In Alberta, total withdrawals increased by 18 % by 2050 in NZDACSSP2, with 71 % of the increase directly associated with DAC operations and the remainder stemming from additional electricity generation and modest increases in irrigation. Saskatchewan saw the largest relative increase in total withdrawals (74 % above NZSSP2), with 79 % of the rise attributable to DAC demand and the rest linked to expanded thermal generation, which increased by 42 % by 2050. Manitoba also saw a minor increase (~3 %) in withdrawals for similar reasons. Finally, as the main source of water for these provinces, the Saskatchewan-Nelson basin experienced the largest increase in total withdrawals (19 %) compared to NZSSP2 by 2050, as presented in the third column of Fig. 4. Finally, the withdrawal patterns described above were the same in the SSP5 versions of the NZ and NZDAC scenarios.

4.2.3. Water consumption in the NZ scenarios

National water consumption increased in NZSSP2 compared to the REF_SSP2, as presented in Fig. 5. The rise was primarily driven by changes in the electricity and irrigation sectors, which saw 17 % and 19 % higher consumption by 2050, respectively. Two key dynamics explain these increases. First, net-zero policies led to a shift toward clean energy sources that are more water consumptive, most prominently hydropower generation, which increased by 10 % nationally by 2050 and contributed to elevated evaporative losses, and irrigation consumption, which rose with expanded production of purpose-grown biomass crops.

Compared to REF_SSP2, water consumption increased in all provinces, although the magnitude varied depending on the sectoral shifts described earlier. In British Columbia, water consumption increased by 18 % in 2050 because of the rise in hydropower generation (7 %) and biomass production (281 %) from river basins within its boundaries. Consumption for electricity generation and irrigation increased most significantly in the Mackenzie, Fraser and Pacific and Arctic basins, as shown in the second column of Fig. 6. Similarly, the electricity sector consumed more water in the Hudson Bay of Quebec and the Churchill basin in Newfoundland and Labrador, as well as the Saskatchewan-Nelson basin in the three prairie provinces, where hydropower generation increased by 10 %, 7 %, and 19 %, respectively. Uniquely, the adoption of CCS technologies in NZSSP2 drove the increase in consumption in Alberta, where 93 % of the thermal power generation was produced by CCS-equipped power plants by 2050. Finally, Nova Scotia and Prince Edward Island experienced the highest percentage increase in water consumption in NZSSP2 because of biomass irrigation. Similar to the withdrawals, NZSSP5 showed the same patterns as the NZSSP2 scenario, but with higher overall consumption as demonstrated in Figs. 5 and 6.

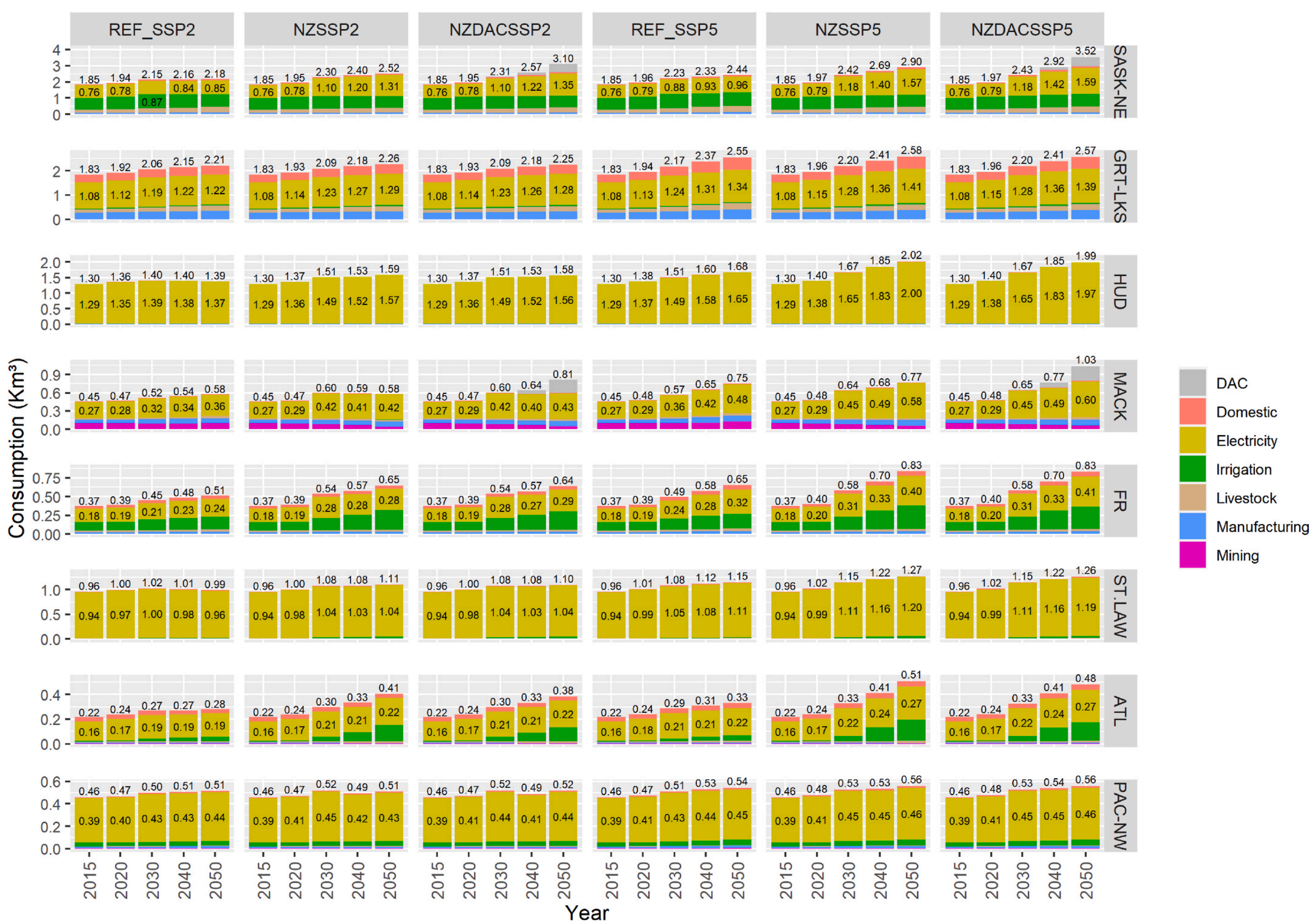

Fig. 6. Water Consumption by sector for river basins with the highest withdrawals in all scenarios between 2015 and 2050
*SASK-NEL: Saskatchewan Nelson, GRT-LKS: Great Lakes, HUD: Hudson, MACK: Mackenzie, FR: Fraser, ST. LAW: Saint Lawerence, ATL: Atlantic, PAC_NW: Pacific Northwest
Text shows Consumption by highest Consumption sector on bar charts and total withdrawals above each bar.

4.2.4. *Water consumption in the NZDAC scenarios*

Water consumption was 7 % higher nationally in NZDACSSP2 than NZSSP2 by 2050, primarily because of the high consumptive water use of DAC systems and an increase in electricity production from hydropower. Similar to withdrawals, DAC deployment in Alberta and Saskatchewan led to 29 % and 91 % higher water consumption, respectively, by 2050 compared to NZSSP2, as illustrated in Fig. 5. In SK, the increase was partially driven by the electricity sector, where water consumption rose by 22 % driven by a 22 % increase in hydropower generation, mainly from the Saskatchewan-Nelson basin.

In contrast, biomass production was lower under NZDACSSP2 because of a reduced reliance on BECCS for negative emissions. Therefore, irrigation water consumption in Nova Scotia and Prince Edward Island, sourced from the Atlantic basin, was 14 % lower in 2050 than in NZSSP2.

4.3. *International trade and global impacts of Canadian water resources*

4.3.1. *Agricultural virtual water exports*

In the reference scenario, REF_SSP2, greater global demands for Canadian food and feed crops, primarily oil crops, wheat, fodder herbs, grains, and biomass increased national virtual water exports by 61 % from 2015 to 2050, as shown in Fig. 7. Oil crops were the largest contributor to this increase, with their use as animal feed rising by 89 %, and as food by 26 % across the other 31 global regions in the model over the same period. At the basin level, this greater demand resulted in significantly higher GVW exports, particularly from the Saskatchewan-Nelson and Great Lakes basins, which are Canada's two largest sources of agricultural virtual water exports. Specifically, by 2050, GVW exports increased by 58 % in the Saskatchewan-Nelson basin and by 28 % in the Great Lakes basin. REF_SSP5 exhibited higher GVW exports than REF_SSP2, particularly with oil crops, because of higher food demands with larger populations in these scenarios.

Global efforts to achieve net-zero drove substantial changes in land use and energy systems, which in turn impacted global demands for Canadian products. In the NZSSP2 scenario, global consumption of oil crops as feed fell by 24 % and for biomass oil production by 30 % compared to REF_SSP2 in 2050. These reductions reflected a broader shift in land use in global mitigation pathways. Increasing land allocation to biomass cultivation and afforestation caused the area available for pasture to decline, which reduced livestock production and the associated demand for feed crops, including oil crops. At the same time,

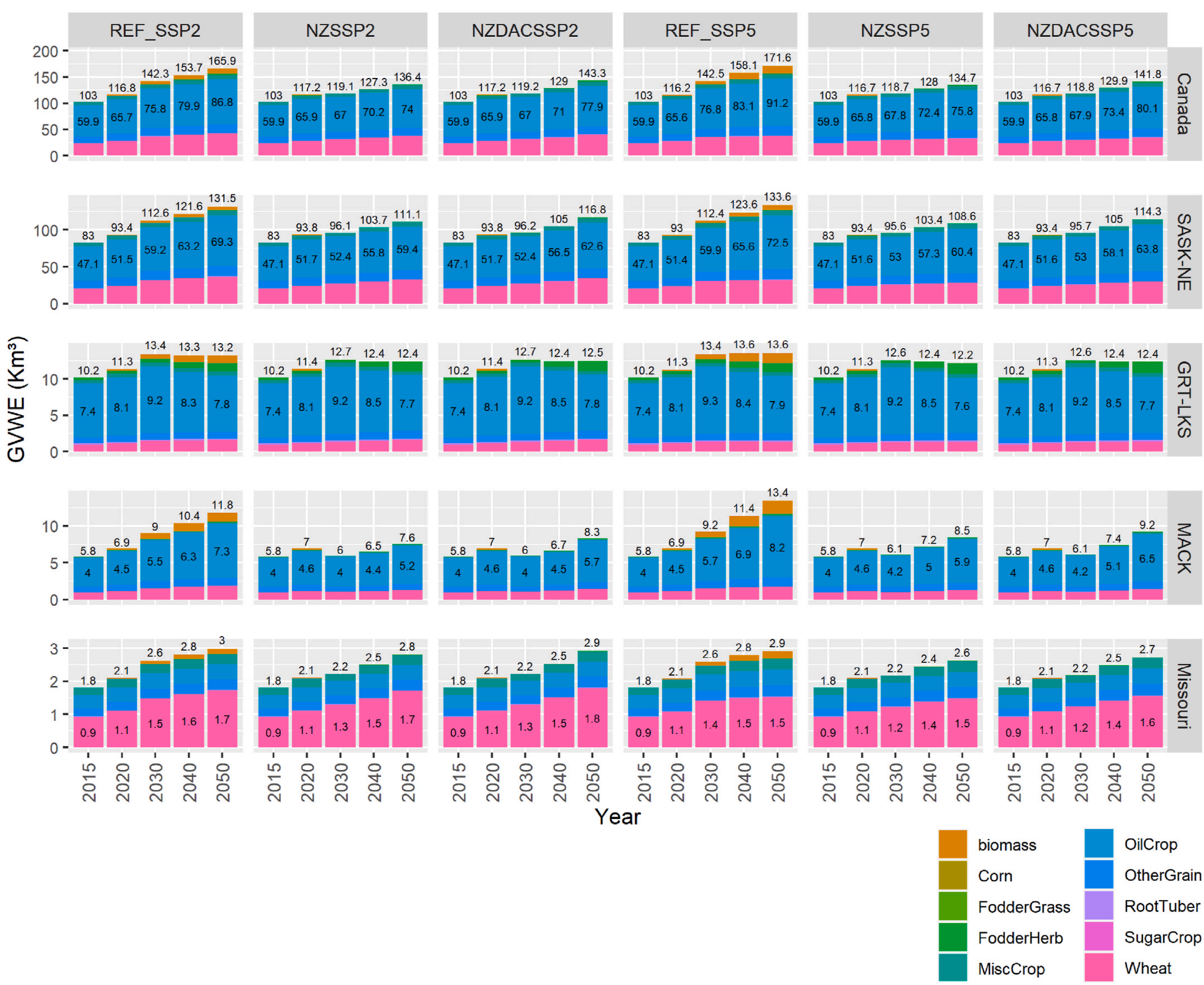

Fig. 7. Greatest green virtual water exports by crop and river basin for all scenarios between 2015 and 2050
*SASK-NE: Saskatchewan Nelson, GRT-LKS: Great Lakes, MACK: Mackenzie, Missouri: Missouri
Text shows Water Exports for highest Sector on bar charts and total Exports above each bar.

oil crops became less competitive as an energy feedstock, since energy systems increasingly shifted toward purpose-grown biomass, favored for its mitigation potential, and other low-carbon fuels. These combined shifts led to reduced Canadian oil crop production and exports, resulting in an 18 % decline in national GVW exports by 2050. As the main oil crop-producing region, the Saskatchewan–Nelson basin experienced a 15 % drop in oil crop-related GVW exports compared to REF_SSP2.

The introduction of DAC technologies in NZDACSSP2 reduced the global reliance on BECCS as the primary negative emissions technology, relatively easing the land-use competition that constrained food and feed crop production under NZSSP2. This shift resulted in a modest rebound in Canadian oil crop exports, which were 5 % higher compared to NZSSP2 by 2050, although they remained below reference scenario levels, since overall structural changes to global food and energy systems continued to limit the role of oil crops in future trade. International trade effects on BVW exports matched most of the described impacts for GVW exports, but were significantly lower since most (~98 % by 2050) Canadian agricultural production was rainfed. Refer to SI5.2 for further analysis on BVW exports.

4.3.2. *Electricity virtual water exports*

In the reference scenario, the U.S. demand for Canadian electricity, primarily from hydropower-producing provinces, peaked by 2030 under REF_SSP2 before gradually declining as shown in Fig. 8. This trade was driven by economic considerations, since importing hydropower remained more cost-effective for the U.S. than expanding domestic generation. In 2015, Canadian EVW exports to the U.S. originated mainly from Quebec (57 %), British Columbia (19 %), Manitoba (17 %), and Ontario (5 %). After 2030, total EVW exports began to decline, primarily due to reduced exports from Quebec as the relative cost of hydropower increased compared to alternative electricity sources.

Net-zero policies in the U.S. led to a notable increase in its demand for Canadian hydropower. As a result, Canadian EVW exports remained consistently higher in NZSSP2 compared to REF_SSP2, and reached 24 % above reference scenario levels by 2050. EVW exports from Quebec peaked in 2030 and declined thereafter, but remained higher throughout the period than in REF_SSP2, as U.S. mitigation policies raised domestic energy prices and made Canadian hydropower relatively more competitive. British Columbia's EVW exports increased by 46 % by 2050, driven by higher hydropower production, while Manitoba's exports also rose by 20 % relative to REF_SSP2. Incorporating DAC into net-zero policies resulted in minimal change to the total volume of Canadian EVW exports to the U.S. by 2050 compared to NZSSP2. Finally, EVW exports were greater in both NZSSP5 and NZDACSSP5 scenarios, with a milder decline post-2030, because of elevated electricity demands in the U.S. under these scenarios.

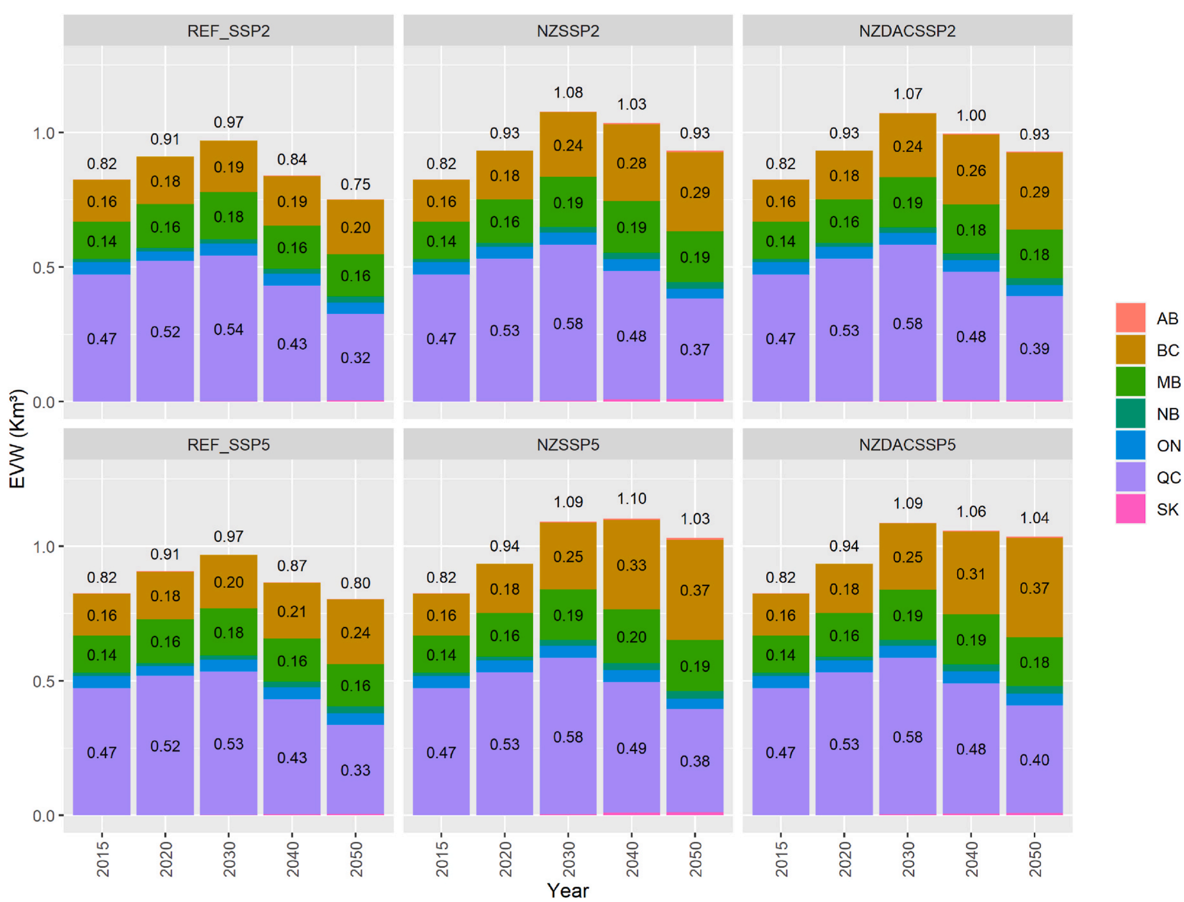

Fig. 8. Electricity virtual water exports from Canada to the united states by exporting province during the study period for all 6 scenarios
* AB: Alberta, BC: British Columbia, MB: Manitoba, NB: New Brunswick, ON: Ontario, QC: Quebec, SK: Saskatchewan
Text shows Water Exports for the top Three Exporting Provinces on bar charts and total Exports above each bar.

5. Conclusions

This study presented trajectories to 2050 of Canadian water use under local and global deep decarbonization scenarios developed with an integrated assessment model, GCAM-Canada, that simulates the linkages among the energy, land, and water systems at subnational scales. The analysis examined how local energy and land use decisions, and their associated water implications, evolved under reference socioeconomic pathways and in response to additional net-zero climate policy interventions. An important aspect of this study is its quantification of the potential impacts of widespread direct air capture technology adoption on subnational water use. Finally, we investigated how global decarbonization influences local water resources in Canada through changes in international demands for agricultural products and electricity, using a virtual water trade framework.

In response to research question 1, we found a 26 % decrease in total national water withdrawals from 2015 to 2050 under the reference scenario (REF_SSP2), in the absence of climate policies, but with substantial variation across provinces and river basins. The provinces of Ontario and Alberta mirrored the national decline with 50 % and 15 % reductions respectively, as the replacement of older cooling technologies by less water-intensive cooling systems in new power plants proved more influential on water withdrawals than rises in domestic and manufacturing water demands from population growth. In contrast, the domestic and manufacturing sectors dominated water withdrawals in British Columbia, Quebec, Manitoba, and Saskatchewan, which increased by 13–31 % with population growth. Water consumption also rose for the same period nationally (+18 %), provincially, and at the river basin level, mainly through evaporative losses from expanding hydropower reservoirs. The higher growth, more technologically focused SSP5 scenarios produced uniformly higher withdrawals and consumption by the end of the study period, even with assumed improvements in water use efficiency. The results of the reference scenario show that the spatial heterogeneity of sectoral water use, in absence of climate policies, was driven by differences in energy mix, demographic growth, and hydropower capacity, and led to uneven regional outcomes, even under shared national scale assumptions, which reinforces the importance of subnational assessments when evaluating long-term water use projections.

The implementation of net-zero policies – associated with research question 2 – met climate goals but produced a potential tradeoff in most provinces, with higher water withdrawals, consumption, or both compared to the reference scenarios by 2050. We found that these policies intensified electricity production from renewable sources, diminished reliance on fossil fuels, and increased electricity consumption across Canada (+17 % compared to REFSSP2) with a corresponding increase in water consumption by hydropower-producing provinces. Moreover, net-zero policies incentivized biomass production (+289 % from irrigated lands compared to REFSSP2) as a clean energy source, which increased irrigation withdrawals and consumption over the reference scenario, notably in British Columbia (+67 %), Nova Scotia and Prince Edward Island (+280 %). Solely in Alberta, net-zero policies decreased water withdrawals from the Saskatchewan-Nelson (−14 %) and Mackenzie basins (−27 %) largely through the retirement of coal-fired power plants and their water-intensive cooling systems, combined with a greater reliance on wind energy. Overall, the spatially heterogenous effects of decarbonization policies on sectoral water use at provincial and river basin scales underlines the importance of local context when formulating climate strategies.

In addressing Research Question 3, we found that adopting direct air capture technologies as part of net-zero policies increased withdrawals and consumption considerably compared to NZSSP2 in Alberta (by 18 % and 29 %) and Saskatchewan (by 74 % and 91 %), where the technology was deployed. In addition to the water intensive nature of the technology, direct air capture led to, 1) greater electricity demands in the western provinces, which drove an increase in water withdrawals and consumption, and 2) a reduction in land use change and biomass cultivation in the eastern provinces. Specifically, the direct air capture technology presented another option for emissions reductions in the net-zero scenario, reducing the reliance on biomass with carbon capture and storage as the primary carbon removal option, and in turn reduced irrigation withdrawals and consumption, especially in Nova Scotia and Prince Edward Island from the Atlantic basin (−14 %) and in British Columbia (−8 %) from the Fraser and Pacific and Arctic basins. Localized increases in water use highlight how the spatial deployment of carbon removal technologies can alter regional water demands, even when national-level changes remain modest.

Finally, in addressing Research Question 4 on the effects of global decarbonization on local water resources, we found that population growth across all scenarios increased international demand for Canadian food and feed crops. The reference REF_SSP2 scenario produced a significant increase in virtual green (+61 %) and blue water (+25 %) exports from 2015 to 2050. However, net-zero policies reduced the green virtual water exports compared to REF_SSP2 (−18 % in 2050), because of a global increase in purpose-grown domestic biomass production that reduced global demands for liquid biofuels produced from oil crops. The global allocation of land resources to biomass also reduced grazing land availability and decreased feed demands, which decreased crop exports from Canadian basins. Furthermore, global efforts to achieve net-zero incentivized the U.S. demand for electricity from clean sources, particularly from hydropower producing provinces including Quebec, British Columbia, and Manitoba, leading to 20 %–46 % higher electricity virtual water exports in these provinces under NZSSP2. These findings demonstrate the importance of incorporating the effects of global drivers on local water resources via international trade for a complete assessment of future water use trajectories under decarbonization scenarios.

Future work should address the effects of climate change and projected temperature increases on both water use coefficients and sectoral demands. While this study explored potential water use tradeoffs under climate policy scenarios, it did not explicitly model how rising temperatures could influence demands across sectors, such as agriculture (via higher evapotranspiration), energy (for cooling or through evaporation from reservoirs), and domestic use. Additionally, warming-related impacts on agricultural yields were not considered, despite their potential to indirectly affect irrigation intensity and land use. Including temperature-driven effects on water demand would increase certainty in the reported values of the potential climate policy tradeoffs reported in this study.

Spatially, our study assessed future water demands at relatively coarse river basin scales. Future research could improve water stress estimation by disaggregating demand projections to finer spatial units, such as subbasins or watersheds, particularly in regions where water use is expected to rise. To support such analyses, future water supply could also be evaluated by running the global hydrologic model under a range of climate forcings, enabling more detailed assessments of water availability and stress under different climate and policy scenarios.

Our climate pathways to net-zero represented economically efficient solutions and were also in part informed by local historical energy preferences; however, energy policy is typically political which undoubtedly influences future pathways to net-zero. A possible approach for future studies is to explore scenarios with different paths to the same goal. Moreover, our study assumed a nationally coordinated policy approach in which provinces contribute cooperatively to a common target. Alternative policy configurations, including decentralized or province-led strategies, could also lead to different outcomes. Exploring the sensitivity of water use to these different institutional arrangements represents another important direction for future work.

Finally, improving the sectoral granularity of the model would strengthen future assessments. In GCAM-Canada, the industrial sector is currently represented as a single aggregated entity with a generic industrial output. Disaggregating this sector into distinct manufacturing subsectors, each with its own technological options, emissions trajectories, trade structures, and water use profiles, would enable a more accurate representation of industrial water demands. It would also make it possible to estimate virtual water associated with manufactured goods, which is absent from the current analysis. Additionally, while the electricity trade structure in GCAM-Canada represents an important advancement by enabling the estimation of electricity virtual water flows, further improvements are needed. Integrating GCAM-Canada with GCAM-USA to represent province-to-state electricity trade would enhance the spatial realism of electricity virtual water assessments.

CRediT authorship contribution statement

Osama Younis: Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Evan G.R. Davies:** Writing – review & editing, Supervision, Funding acquisition, Formal analysis, Conceptualization. **Diego V. Chiappori:** Writing – review & editing, Methodology, Investigation, Conceptualization. **Matthew Binsted:** Writing – review & editing, Supervision, Methodology, Conceptualization. **Muhammad-Shahid Siddiqui:** Writing – review & editing, Investigation, Conceptualization. **Evan J. Arbuckle:** Writing – review & editing, Investigation. **Nick Macaluso:** Writing – review & editing, Investigation, Conceptualization.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work the authors used Chat-GPT in order to check language and improve the readability and flow of the manuscript. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Evan Davies reports financial support was provided by Canada First Research Excellence Fund. Diego V. Chiappori reports a relationship with Environment and Climate Change Canada that includes: employment. Muhammad-Shahid Siddiqui reports a relationship with Environment and Climate Change Canada that includes: employment. Nick Macaluso reports a relationship with Environment and Climate Change Canada that includes: employment. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2025.126416.

Data availability

Data will be made available on request.

References

Agrawal, N., Ahiduzzaman, Md, Kumar, A., 2018. The development of an integrated model for the assessment of water and GHG footprints for the power generation sector. Appl. Energy 216, 558–575. https://doi.org/10.1016/j.apenergy.2018.02.116.

Agrawal, N., Patrick, T., Davis, M., Ahiduzzaman, M., Kumar, A., 2022. Analysis of Canada's water use: tracing water flow from source to end use. Can. Water Resour. J./Revue canadienne des ressources hydriques. 47, 1–21. https://doi.org/10.1080/07011784.2021.1994884.

Agriculture and Agri-Food Canada (AAFC), 2024. Overview of Canada's Agriculture and agri-food Sector. https://agriculture.canada.ca/en/sector/overview.

Ali, B., 2018. Forecasting model for water-energy nexus in Alberta, Canada. Water-Energy Nexus 1 (2), 104–115. https://doi.org/10.1016/j.wen.2018.08.002.

Allan, J., Lant, C., 2003. Virtual water - the water, food, and trade nexus. Useful concept or misleading metaphor? Water International - WATER INT 28, 106–113. https://doi.org/10.1080/02508060.2003.9724812.

Allan, J.A., 1994. Overall perspectives on countries and regions. In: Rogers, P., Lydon, P. (Eds.), Water in the Arab World: Perspectives and Prognoses. Harvard University Press, pp. 65–100.

Arbuckle, E.J., 2023. Integration of Subnational Endogenous Hydropower into the Global Change Analysis Model for Canada. University of Alberta, Thesis. https://doi.org/10.7939/r3-0ap8-6s32.

Ashktorab, N., Zibaei, M., 2021. Future virtual water flows under climate and population change scenarios: focusing on its determinants. J. Water Clim. Change 13. https://doi.org/10.2166/wcc.2021.190.

Bakken, T.H., Killingtveit, Å., Alfredsen, K., 2017. The water footprint of hydropower production-state of the art and methodological challenges. Glob Chall 1 (5), 1600018. https://doi.org/10.1002/gch2.201600018.

Bergero, C., Binsted, M., Younis, O., Davies, E., Siddiqui, M.-S., Xing, R., Arbuckle, E., Chiappori, D., Fuhrman, J., McJeon, H., Macaluso, N., 2022. Technology, technology, technology: an integrated assessment of deep decarbonization pathways for the Canadian oil sands. Energy Strategy Rev. 41, 100804. https://doi.org/10.1016/j.esr.2022.100804.

Bijl, D.L., Bogaart, P.W., Kram, T., Vries, B.D., Vuuren, D.V., 2016. Long-term water demand for electricity, industry and households. Environ. Sci. Pol. 55, 75–86.

Binsted, M., Iyer, G., Patel, P., Graham, N., Ou, Y., Khan, Z., Kholod, N., Narayan, K., Hejazi, M., Kim, S., Calvin, K., Wise, M., 2022. GCAM-USA v5.3_water_dispatch: integrated modeling of subnational U.S. energy. water, and land systems within a global framework. https://doi.org/10.5194/gmd-2021-197.

Calvin, K., Patel, P., Clarke, L., Asrar, G., Bond-Lamberty, B., Cui, R., Di Vittorio, A., Dorheim, K., Edmonds, J., Hartin, C., Hejazi, M., Horowitz, R., Iyer, G., Kyle, P., Kim, S., Link, R., McJeon, H., Smith, S., Snyder, A., Wise, M., 2019. GCAM v5.1: representing the linkages between energy, water, land, climate, and economic systems. Geosci. Model Dev. (GMD) 12, 677–698. https://doi.org/10.5194/gmd-12-677-2019.

Chaturvedi, V., Hejazi, M., Edmonds, J., Clarke, L., Kyle, P., Davies, E., Wise, M., 2013. Climate mitigation policy implications for global irrigation water demand. Mitig. Adapt. Strategies Glob. Change 20. https://doi.org/10.1007/s11027-013-9497-4.

Chen, L., Gan, X., Yi, B., Qin, Y., Lu, L., 2022. Domestic water demand prediction based on system dynamics combined with social-hydrology methods. Nord. Hydrol 53. https://doi.org/10.2166/nh.2022.051.

Chiappori, D.V., Davies, E.G.R., Binsted, M., Bergero, C., Stelmach, T., Siddiqui, M.S., Younis, O., Arbuckle, E.J., Macaluso, N., Under review. Modelling Canada's path to net-zero: evaluating policy strategies for 2050 with GCAM-Canada. Energy Strategy Rev.

Correa, M., Salmoral, G., Rey, D., Knox, J.W., Graves, A., Melo, O., Foster, W., Naranjo, L., Zegarra, E., Johnson, C., Viteri Salazar, O., Yan, X., 2022. A novel modelling toolkit for unpacking the water-energy-food-environment (WEFE) nexus of agricultural development. Renew. Sustain. Energy Rev. 159. https://doi.org/10.1016/j.rser.2022.112182.

Davies, E., Kyle, P., Edmonds, J., 2013. An integrated assessment of global and regional water demands for electricity generation to 2095. Adv. Water Resour. 52, 296–313. https://doi.org/10.1016/j.advwatres.2012.11.020.

Duarte, R., Pinilla, V., Serrano, A., 2014. Looking backward to look forward: water use and economic growth from a long-term perspective. Appl. Econ. 46 (2), 212e224.

Environment and Climate Change Canada (ECCC), 2022. Exploring Approaches for Canada's Transition to Net-Zero Emissions. Report. https://unfccc.int/sites/default/files/resource/LTS%20Full%20Draft_Final%20version_oct31.pdf.

Environment and Climate Change Canada (ECCC), 2024. Greenhouse Gas Emissions: Canadian Environmental Sustainability Indicators.

Felder, F., 2014. Climate change mitigation and the global energy system, 25 vill. Envtl. L.J. 89. Available at: https://digitalcommons.law.villanova.edu/elj/vol25/iss1/3.

Fu, T., Xu, C., Huang, X., 2021. Analysis of virtual water trade flow and driving factors in the European Union. Water 13, 1771. https://doi.org/10.3390/w13131771.

Fuhrman, J., McJeon, H., Patel, P., Doney, S.C., Shobe, W.M., Clarens, A.F., 2020. Food-energy-water implications of negative emissions technologies in a +1.5 oC future. Nat. Clim. Chang. (in press) Online: https://github.com/jayfuhrman/No-Safety-NET-DAC-Modeling.

Fuhrman, J., Clarens, A., Calvin, K., Doney, S.C., Edmonds, J.A., O'Rourke, P., et al., 2021. The role of direct air capture and negative emissions technologies in the shared socio-economic pathways towards+ 1.5° C and+ 2° C futures. Environ. Res. Lett. 16 (11), 114012.

Ganji, F., Liu, L., Fellows, S., 2024. Implications of climate change mitigation and socio-economic development on the U.S. electric power sector. Energy and Climate Change 5, 100125. https://doi.org/10.1016/j.egycc.2024.100125.

Graham, N., Davies, E.G.R., Hejazi, M., Calvin, K., Kim, S., Helinski, L., Miralles-Wilhelm, F., Clarke, L., Kyle, P., Patel, P., Wise, M., Vernon, C., 2018. Water sector assumptions for the shared socio-Economic pathways in an integrated modeling framework. Water Resour. Res. 54. https://doi.org/10.1029/2018WR023452.

Graham, N., et al., 2020a. Humans drive future water scarcity changes across all shared Socio-economic pathways. Environ. Res. Lett. 15. https://doi.org/10.1088/1748-9326/ab639b.

Graham, N., et al., 2020b. Future changes in the trading of virtual water. Nat. Commun. 11. https://doi.org/10.1038/s41467-020-17400-4.

Graham, N., Iyer, G., Wise, M., Hejazi, M., Wild, T., 2021. Future evolution of virtual water trading in the United States electricity sector. Environ. Res. Lett. 16, 124010. https://doi.org/10.1088/1748-9326/ac3289.

Gupta, A., Davis, M., Kumar, A., 2021. An integrated assessment framework for the decarbonization of the electricity generation sector. Appl. Energy 288, 116634. https://doi.org/10.1016/j.apenergy.2021.116634.

Hejazi, M., Edmonds, J., Chaturvedi, V., Davies, E.G.R, Eum, J., 2013. Scenarios of global municipal water use demand projections over the 21st century. Hydrological Sciences Journal/Journal des Sciences Hydrologiques 58, 1–20, 10.1c080/02626667.2013.772301.

Hejazi, M., Edmonds, J., Clarke, L., Kyle, P., Davies, E., Chaturvedi, V., Wise, M., Patel, P., Eom, J., Calvin, K., Moss, R., Kim, S., 2014a. Long-term global water projections using six socio-economic scenarios in an integrated assessment modeling framework. Technol. Forecast. Soc. Change 81, 205–226. https://doi.org/10.1016/j.techfore.2013.05.006.

Hejazi, M., Edmonds, J., Clarke, L., Kyle, P., Davies, E., Chaturvedi, V., Eom, J., Wise, M., Patel, P., Calvin, K., 2014b. Integrated assessment of global water scarcity over the 21st century - part 2: climate change mitigation policies. Hydrol. Earth Syst. Sci. Discuss. 10, 3383–3425. https://doi.org/10.5194/hessd-10-3383-2013.

Huang, Z.W., Hejazi, M., Tang, Q.H., Vernon, C., Liu, Y.L., Chen, M., Calvin, K., 2019. Global agricultural green and blue water consumption under future climate and land use changes. J. Hydrol. 574. https://doi.org/10.1016/j.jhydrol.2019.04.046.

IPCC, 2023. Summary for policymakers. In: Lee, H., Romero, J. (Eds.), Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team. IPCC, Geneva, Switzerland, pp. 1–34. https://doi.org/10.59327/IPCC/AR6-9789291691647.001.

JGCRI, 2022. GCAM v6 Documentation: Model Overview. Retrieved from. https://jgcri.github.io/gcam-doc/overview.html.

Kim, S., Hejazi, M., Liu, L., Calvin, K., Clarke, L., Edmonds, J., Kyle, P., Patel, P., Wise, M., Davies, E.G.R., 2016. Balancing global water availability and use at basin scale in an integrated assessment model. Clim. Change 136. https://doi.org/10.1007/s10584-016-1604-6.

Kuling, K.B., Shivakumar, T., Brinkerink, A., Maarten Niet, T., 2022. Applying the open-source climate, land, energy, and water systems (CLEWs) model to Canada. Energy Strategy Rev. 44, 100929. https://doi.org/10.1016/j.esr.2022.100929.

Kyle, P., Davies, E.G.R., Dooley, J.J., Smith, S.J., Clarke, L.E., Edmonds, J.A., Hejazi, M., 2013. Influence of climate change mitigation technology on global demands of water for electricity generation. Int. J. Greenh. Gas Control 13, 112–123. https://doi.org/10.1016/j.ijggc.2012.12.006.

Li, X.Y., Vernon, C., Hejazi, M., Link, R., Feng, L.Y., Liu, Y.L., Rauchenstein, L., 2017. Xanthos – a global hydrologic model. J. Open Res. Software 5. https://doi.org/10.5334/jors.181.

Liu, L., Hejazi, M., Patel, P., Kyle, P., Davies, E.G.R., Zhou, Y.Y., Clarke, L., Edmonds, J., 2015. Water demands for electricity generation in the U.S.: modeling different scenarios for the water–energy nexus. Technol. Forecast. Soc. Change 94, 318–334. https://doi.org/10.1016/j.techfore.2014.11.004.

Liu, X.L., Xiong, R., Guo, P.B., Nie, L., Shi, Q.Q., Li, W.T., Cui, J., 2022. Virtual water flow pattern in the yellow River Basin, China: an analysis based on a multiregional input–output model. Int. J. Environ. Res. Publ. Health 19 (12), 7345. https://doi.org/10.3390/ijerph19127345.

Macknick, J., Newmark, R., Heath, G., Hallett, K.C., 2012. Operational water consumption and withdrawal factors for electricity generating technologies: a review of existing literature. Environ. Res. Lett. 7, 045802. https://doi.org/10.1088/1748-9326/7/4/045802.

Maheu, A., 2009. Energy choices and their impacts on demand for water resources: an assessment of current and projected water consumption. In: Global Energy Production. McGill University, Montreal, Canada.

McCollum, D., et al., 2018. Connecting the sustainable development goals by their energy inter-linkages. Environ. Res. Lett. 13. https://doi.org/10.1088/1748-9326/aaafe3.

Mekonnen, M.M., Hoekstra, A.Y., 2010. The green, blue and grey water footprint of farm animals and animal products. In: Appendices. Appendix IV. Drinking and Service Water Footprint per Animal (litre/day). Value of Water Research Report Series No. 48, vol. 2. UNESCO-IHE Institute for Water Education. Link.

Mekonnen, M.M., Hoekstra, A.Y., 2011. The green, blue and grey water footprint of crops and derived crop products. Hydrol. Earth Syst. Sci. 15, 1577–1600.

Moraes Coraça, G., Davis, M., Kumar, A., 2025. "Long-term integrated assessment of the water, GHG, and cost impacts of a transition to low-carbon hydrogen production: a case study for Canada. J. Clean. Prod. 491, 144758. https://doi.org/10.1016/j.jclepro.2025.144758. ISSN 0959-6526.

Natural Resources Canada, 2024. "Energy Fact Book 2024-2025". Report. https://energy-information.canada.ca/sites/default/files/2024-10/energy-factbook-2024-2025.pdf.

Nechifor, V., Winning, M., 2017. Projecting irrigation water requirements across multiple socio-economic development futures—A global CGE assessment. Water Resour. Econ. 20, 16–30.

O'Neill, Brian, et al., 2014. The roads ahead: narratives for shared socio-economic pathways describing world futures in the 21st century. Glob. Environ. Change 42. https://doi.org/10.1016/j.gloenvcha.2015.01.004.

Ou, Y., Iyer, G., McJeon, H., Cui, R., Zhao, A., O'Keefe, K., Zhao, M., Qiu, Y., Loughlin, D., 2023. State-by-state energy-water-land-health impacts of the US net-zero emissions goal. Energy and Climate Change 4, 100117. https://doi.org/10.1016/j.egycc.2023.100117.

Pittock, J., 2011. National climate change policies and sustainable water management: conflicts and synergies. Ecol. Soc. 16 (2). https://doi.org/10.5751/ES-04037-160225.

Riahi, K., et al., 2017. The shared socio-economic pathways and their energy, land use, and greenhouse gas emissions implications: an overview. Glob. Environ. Change 42, 153–168.

Sartori, M., Schiavo A., S. Fracasso, Riccaboni, M., 2017. Modeling the future evolution of the virtual water trade network: a combination of network and gravity models. Adv. Water Resour. 110, 538–548. https://doi.org/10.1016/j.advwatres.2017.05.005.

Statistics Canada, 2023. Agricultural Water Survey, 2022. May 2024. https://www150.statcan.gc.ca/n1/daily-quotidien/231017/dq231017c-eng.htm.

Turner, S., Ng, J., Galelli, S., 2017. Examining global electricity supply vulnerability to climate change using a high-fidelity hydropower dam model. Sci. Total Environ. 590. https://doi.org/10.1016/j.scitotenv.2017.03.022.

Turner, P.A., Field, C.B., Lobell, D.B., et al., 2018. Unprecedented rates of land-use transformation in modelled climate change mitigation pathways. Nat. Sustain. 1, 240–245. https://doi.org/10.1038/s41893-018-0063-7.

Wild, T., Khan, Z., Zhao, M., Suriano, M., Bereslawski, J., Roberts, P., Casado, J., Novillo, G., Marcelo, Clarke, L., Hejazi, M., Miralles-Wilhelm, F., Muñoz-Castillo, R., Vernon, C., Snyder, A., Yarlagadda, B., Birnbaum, A., Lamontagne, J., White, D., Ojeda-Matos, G., 2021a. The implications of global change for the co-evolution of Argentina's integrated energy-water-land systems. Earths Future 9. https://doi.org/10.1029/2020EF001970.

Wild, T., Khan, Z., Clarke, L., Hejazi, M., Bereslawski, J., Suriano, M., Roberts, P., Casado, J., Miralles-Wilhelm, F., Gavino-Novillo, M., Muñoz-Castillo, R., Moreda, F., Zhao, Mengqi, Y., Brinda, L., Jonathan, Birnbaum, A., 2021b. Integrated energy-water-land nexus planning in the Colorado River Basin (Argentina). Reg. Environ. Change 21. https://doi.org/10.1007/s10113-021-01775-1.

Wu, L., Elshorbagy, A., Pande, S., Zhuo, L., 2021. Trade-offs and synergies in the water-energy-food nexus: the case of Saskatchewan, Canada. Resour. Conserv. Recycl. 164, 105192. https://doi.org/10.1016/j.resconrec.2020.105192.

Younis, O., Davies, E.G.R., 2023. A quantification and analysis of historical sectoral and regional water withdrawals in Canada. Can. Water Resour. J./Revue canadienne des ressources hydriques 49 (1), 40–63. https://doi.org/10.1080/07011784.2023.2224295.

Zeng, Y.J., Liu, D.D., Guo, S.L., Xiong, L.H., Liu, P., Yin, J.B., Wu, Z.H., 2022. A System Dynamic Model to Quantify the Impacts of Water Resources Allocation on water-energy-food-society (WEFS) Nexus. https://doi.org/10.5194/hess-2021-521.

Zhong, R., Chen, A.F., Zhao, D.D., Mao, G.Q., Zhao, X., Huang, H., Liu, J.G., 2023. Impact of international trade on water scarcity: an assessment by improving the Falkenmark indicator. J. Clean. Prod. 385, 135740. https://doi.org/10.1016/j.jclepro.2022.135740.